

DEVELOPMENT OF SPACE INFLATABLE/RIGIDIZABLE STRUCTURES TECHNOLOGY

M.C. LOU and V.A. FERIA
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, CA 91107, USA

1. Abstract

Space inflatable and rigidizable structures technology is one of the emerging technologies that can potentially revolutionize the design and applications of large space structural systems. In the last two years, NASA and its industry and academia partners have made significant progress in addressing important technical challenges for the actual implementation of inflatable structures for space flight systems. A summary assessment on the state of the art of three of the challenges, namely controlled deployment, space rigidization and dynamic modeling and simulation, is presented. Also, two recently developed inflatable structural systems, the inflatable SAR and the NGST inflatable sunshield, are described.

2. Introduction

Launch cost, which is often directly proportional to launch volume and mass, is a significant portion of the life-cycle cost of a space mission. To align with the increasingly stringent budget environment, NASA has been engaging in the development of breakthrough, high-payoff technologies to enable smaller, lighter and yet more capable spacecraft for future missions. One of these, the space inflatable/rigidizable structures technology, has recently received much attention from the mission planners. Many of the NASA missions planned for the next decade will rely on space inflatable structures to achieve their launch volume and mass goals. This is especially true for missions employing spacecraft equipped with certain types of hardware components that require relatively large in-orbit configurations to properly perform their assigned functions. Such components include radar antennas, solar arrays, sunshields, telescope reflectors and aerobrakes. Presently, mechanically deployed structures are used to construct these components to overcome the constraints imposed by fairing size on launch volumes. Compared to these type of structures, space inflatable/rigidizable structures have the advantages of much lighter weight, higher packaging efficiency and, more importantly, higher deployment reliability. It is believed that inflatable/rigidizable structures will replace mechanically deployed structures for many space applications in the foreseeable future.

Depending on how stringent are the configuration control requirements of its intended application, a space inflatable structure may fall into one of the two roughly defined groups: precision structures and non-precision structures. At this time, precision inflatable structures refer mainly to telescope reflectors that operate in near infrared and even optical wavelengths. These reflectors need to have very large apertures with highly precise configuration accuracy, usually in the micro or sub-micron range. Before these large-aperture precision reflectors can be implemented for space missions, many technical challenges, such as high-quality films, coating on thin films, precision manufacturing on earth, and in-orbit configuration control, need to be resolved. On the other hand, the non-precision inflatable structures currently cover a wide range of structural systems formed by tubular elements. These include beams, columns, planar frames, and space trusses with applications to radar arrays, solar arrays, sunshield, booms and posts. Although there are also technical challenges to overcome, it is believed that the near-term implementation of non-precision inflatable structures in space missions is a reachable goal. Based on the information known to the authors of this paper, three of the key technical challenges, i.e., controlled deployment, space rigidization, and dynamic modeling and simulation, are discussed below.

3. Controlled Deployment

As revealed by the in-orbit deployment of the Inflatable Antenna Experiment (IAE) flown in May 1996, dynamic motions of uncontrolled inflation deployment of long tubes could be very volatile and unpredictable. Although the IAE successfully completed its in-orbit deployment, this experience has led to major safety and mission reliability concerns. In a space mission, there is a high probability that uncontrolled inflation of the inflatable structures might impinge and damage other flight hardware, such as delicate sensors, optical instruments and pressure vessels, that are located nearby.

Over the past two years, several design concepts have been developed by various researchers to achieve controlled deployment of tubular inflatable structures. One of the early concepts [1] is to use collapsible diaphragms to divide a long inflatable tube into a series of sectional compartments. These diaphragms are flexible enough such that the tube can still be z-folded or rolled up for high packaging efficiency. The inflation deployment process of the tube will be initiated by inflating one selected compartment until it reaches the operating pressure and attains the designed stiffness. At this point, the flow of inflation gas, regulated by check valves or burst disks installed on the diaphragms, will start to inflate the next compartment of the tube. This "sequential" inflation process can achieve stable and predictable deployment of a tubular inflatable structure. Another concept, also described in [1], suggests the use of coil springs of relatively low spring constants. These coil springs are to be embedded in the walls of an inflatable tube that is rolled up before deployment. A stable deployment of the tube is achieved by balancing the inflation pressure and the restoring forces of the springs.

Recognizing that controllability and stability of inflation-deploying structures can be achieved by providing resistive forces to balance the inflation pressure, many innovative design concepts are emerging. For example, the embedded coil springs can

be replaced by Velcro® strips glued to the outside of the tube wall. In addition to being easy to install, the Velcro® strips offer two major distinct advantages. First of all, the tube with Velcro® strips can be packaged in both rolled-up and z-folded configurations. Secondly, unlike the coil springs, the Velcro® strips will not impose any returning forces on the deployed tube when the inflation deployment is completed. It is worth mentioning that Velcro® strips also have had space flight heritage. In the Mars Pathfinder mission, Velcro® strips were employed to slow down the deployment of the landing ramps for the rover. Another example of controlled deployment, proposed and developed by the researchers at L'Garde, involves the use of a mandrel. During the deployment process, the inflating tube is forced to go over an internal guiding mandrel and develop frictional forces to balance the inflation pressure. The application of this mandrel-guided approach to control inflation deployment of a space rigidizable truss has been proposed by L'Garde.

4. Space Rigidization

For any long-term space application, an inflatable structure needs to be rigidized. This is because leaks will be developed through small holes in the walls of the inflatable, created by impacting micrometeoroids and space debris. If the structure is rigidized upon the completion of its inflation deployment, the need to carry a large amount of make-up gas to compensate for leaks can be eliminated.

Since the early 1960s, many researchers have engaged in finding the best rigidization methods for space inflatable structures. These include the development of a number of polymers that can be cured by space environments, such as vacuum, ultraviolet (UV) light, infrared (IR) energy and cold. A summary report on many of these early efforts was given by Schwartz [2], who also pointed out the advantages of simplicity, high reliability and reversibility of several pioneering methods involving solvent loss systems. In a solvent loss system, a volatile plasticizer leaves the impregnated fabric that form the wall of tubular inflatable structure, as soon as the structure is deployed in vacuum. One of the solvent loss systems, which uses a water-gelatin solution, was first suggested in 1966 by Keller et al. [3]. In 1984, Hinson and Keafer [4] described the

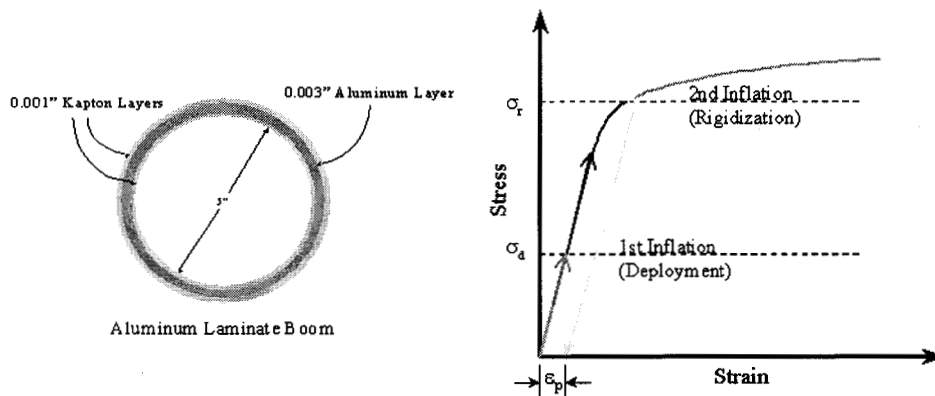


Figure 1. Stretched Aluminum Laminate

self-rigidization process of stretched aluminum laminates. These sandwich laminates are made by bonding thin aluminum foils to polyester films, such as Kapton. While the polyester films provide tear resistance and a gas seal, the aluminum foils are stretched by pressure just above the yield point to provide rigidity of the inflatable structure. Figure 1 illustrates the stretched aluminum laminate method.

The desired features for space rigidization include:

- Easily adaptive to high-efficiency packaging
- Compatible with controlled deployment scheme
- No or low space power required
- No or low in-orbit outgassing or contamination
- Predictable post-rigidization configuration accuracy
- Adaptive to ground handling and testing

The space rigidization methods currently under favorable considerations and/or active development include:

- Stretched aluminum laminate
- Hydro-gel rigidization
- Open-cell foam
- Various polyester coatings cured by space cold, heat, UV or IR

Of these, the stretched aluminum laminate method has currently received much attention. In addition to taking advantage of the inflation system that is already needed for deployment, this method also offers the following distinct advantages: (1) It can accommodate inflatable tubes that are either rolled up or z-folded; (2) It does not require power; and (3) It has negligible level of outgassing. More importantly, both of the two component materials, aluminum and Kapton, of the stretched aluminum laminate have long heritage of space applications. On the other hand, there remains a major shortcoming of the stretched aluminum laminate rigidization method that needs to be overcome. Since, due mainly to packaging constraints, only a very thin (no more than 0.005") aluminum layer can be incorporated in the laminate, the inflatable/rigidizable tubes made of stretched aluminum laminates can only be used to carry relatively low axial loads. For the cases that involve high compression and/or significant bending loads, the thin-walled aluminum laminate tubes tend to fail by local crippling. It is believed that, before the stretched aluminum laminate method can be considered as the preferred rigidization method for general inflatable structures, major improvements in materials selection, laminate lay-up and fabrication processes are needed.

Hydro-gel rigidization is a rigidization method that has potential applications to certain classes of space inflatable structures. This method has been successfully applied by L'Garde to develop an inflatable/rigidizable space truss [5]. The truss (see Figure 2) is formed by tubular elements that are assembled together with complex metal joints. Each tubular element is basically a cylindrical tube that is made of woven graphite fabric and impregnated with a water-soluble resin (hydro-gel). Evaporation of the water content in the impregnated hydro-gel will occur after inflation deployment in vacuum

and the dehydrated hydro-gel rigidizes to give structural stiffness to individual tubular elements. Like other solvent loss systems, one major advantage of the hydro-gel method is that the rigidization process is completely reversible. That is, the rigidized inflatable structure can absorb water, get softened, and be re-rigidized repeatedly to facilitate ground testing and measurements of the flight inflatable structures.

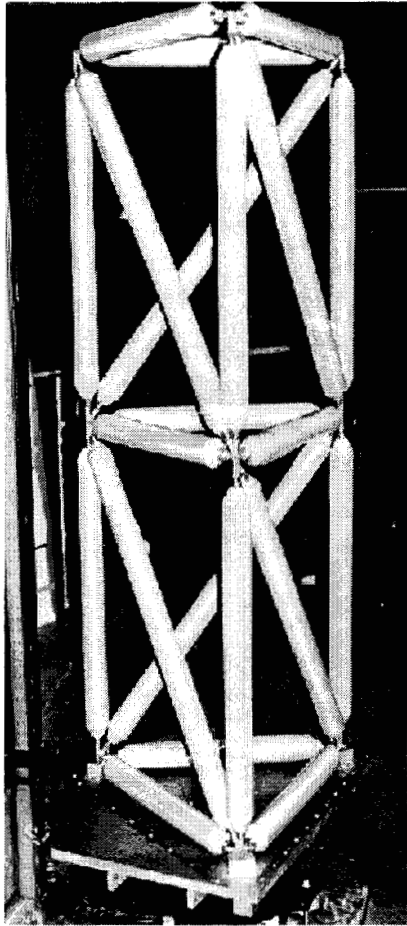


Figure 2. Inflatable/Rigidizable Space Truss

Other on-going space rigidization development efforts known to the authors of this paper include heat-cured coatings (thermoplastic and thermoset) at ILC-Dover, cold rigidization at L'Garde, and UV-cured coating at Adherent Technologies. JPL, working with Mitsubishi Heavy Industries of Japan, is also developing a new type of space rigidizable material, called the Cold Hibernated Elastic/Shape Memory (CHEM) [6]. CHEM is formulated by incorporating shape memory polymers into open-cellular foam. This material has a maximum deployed/stowed volume ratio of 30 and is self-expanded when heated up above its glass transition temperature. This means that a space rigidizable structure made of CHEM does not need an inflation system to deploy.

5. Dynamic Modeling and Simulation

Inflation deployment of an inflatable structure is a complex process that involves interactions between gas flow and flexible membranes. Although many publications on static behavior of inflatable structures exist [e.g., 7, 8 and 9], there is relatively little information on inflation dynamics available in the literature. As one of the early attempts to simulate inflation dynamics, Haug et al. [10] employed an explicit nonlinear crash analysis code to investigate the feasibility of applying airbag deployment

simulation technology to study deployment of a z-folded inflatable antenna reflector. Main et al. [11] conducted a study, which was based on Euler-Bernoulli beam theory in conjunction with finite-element modeling, to determine natural frequencies and damping parameters from model tests of inflated tubes in the near weightlessness of the NASA KC-135 low gravity simulator aircraft.

More recently, several research efforts aimed at gaining fundamental understanding of inflation dynamics have been initiated. Tsoi [12] formulated and developed a MATLAB code to simulate inflation deployment of z-folded inflatable tubes and a "z-

star" toroidal stiffened spherical surface. His simulation showed that the z-folded tubes are inherently unstable. Steele et al. [13] carried out two experimental studies to investigate the forces at the fold line of a z-folded tube and the torque needed to deploy a rolled-up tube. In both experiments, it was observed that regions of nearly constant curvature dominated the deformed tube. This observation permitted a simple approximation for the calculation of the volume of the deformed configuration, which is used in a potential energy formulation of the dynamic motions of the tubes. Details of these experimental and analytical efforts will soon appear in [14 and 15]. At JPL, there is an on-going study effort to model and simulate inflation deployment of flexible tubes equipped with various restrictive devices, including the use of an internal guiding mandrel, for controlled deployment. Progress of this JPL effort will also be reported in the near future [16].

Modeling and simulation of dynamic behavior of the stretched (pre-tensioned) membranes used in the Next Generation Space Telescope (NGST) inflatable sunshield is an endeavor that has recently been undertaken by researchers at the University of Colorado, NASA Goddard Space Flight Center (GSFC) and JPL. This effort is important because NGST will have optical instruments that are extremely sensitive to in-orbit disturbances, including those coming from its large inflatable sunshield. In order to guide the development of system architecture and design of NGST, as well as to predict its in-orbit performance, dynamic responses of stretched membranes need to be accurately characterized.

The most challenging aspect in modeling stretched membranes is the presence of wrinkles. A thin membrane can not carry any compressive loading. When a portion of a membrane is subjected to localized compressions, wrinkles are formed. These wrinkles will redistribute the in-plane stresses and induce geometry changes. Static behavior of wrinkled membranes has been previously studied by Stein and Hedgepeth [17] and Mikulas [18]. More recently, Murphey and Mikulas [19] identified bending as the dominant deformation mechanism resulting in the nonlinear behavior of wrinkled membranes. Another unique aspect of modeling stretched membranes is the need to account for out-of-plane stiffness, called differential stiffness and derived directly from pretensions in the membrane. The current NGST sunshield dynamic modeling considers the effects of both pretension and wrinkles.

6. NGST Sunshield

NASA is currently engaging in technology development for the NGST Mission scheduled to be flown in 2007. This mission, managed by GSFC, envisions a near infrared, 8-meter-aperture telescope to be positioned at L2 orbit for 5 to 10 years. In order to passively cool the telescope to below 60° K for maximum science return, a very large (up to 32-meter by 14-meter) sunshield with multiple-layers of thermal membranes is included in the baseline NGST architecture, see Figure 3. Although both a mechanically deployed and inflatable sunshield are being considered at this time. The inflatable design offers several inherent advantages, including lighter weight and smaller launch volume, over its mechanically deployed counterpart. More importantly,

an inflatable sunshield will be much less complex and has at least one order of magnitude less number of parts than a mechanically deployed sunshield. This much smaller part count leads to higher reliability, and cheaper fabrication and assembly costs.

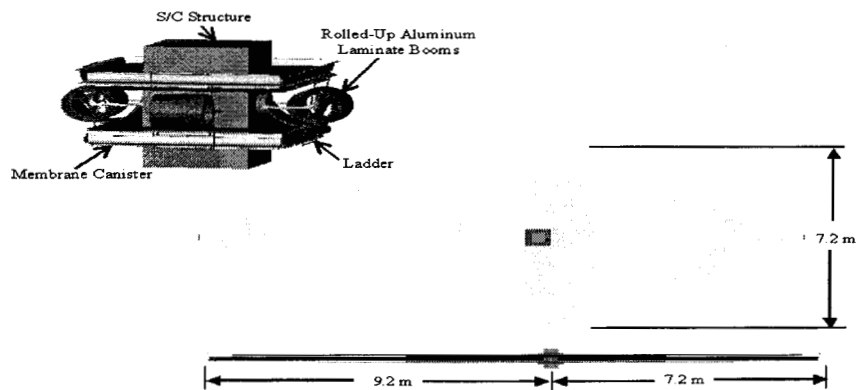


Figure 3. NGST Reference Architecture

One of the major concerns for the incorporation of an inflatable sunshield in the NGST is the potential risk that the deploying sunshield might go through uncontrolled motions and unintentionally impinge and damage the telescope. To address this concern, GSFC and JPL, working with L'Garde and ILC, have developed a 1/2-scale engineering model to demonstrate, among other things, controlled deployment. The NGST sunshield in stowed, half-deployed and fully deployed configurations is shown in Figure 4. This

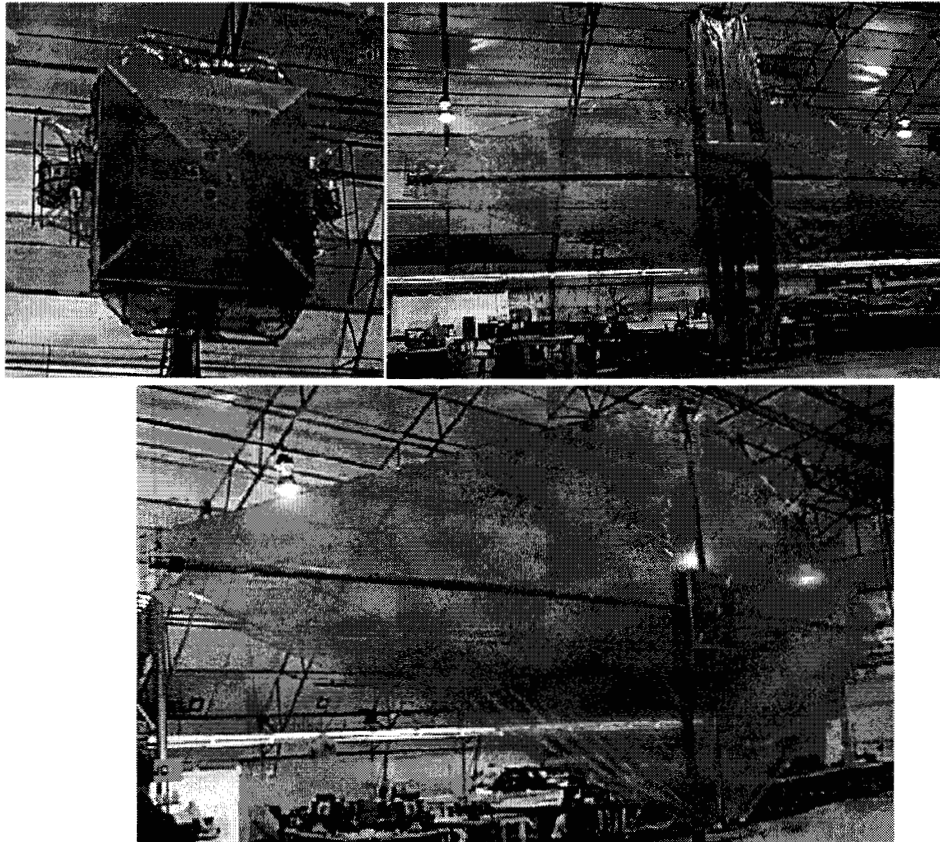


Figure 4. NGST Sunshield in Stowed, Half-Deployed and Fully Deployed Configurations.

Velcro® strips, whereas the membranes were held in position by spring-loaded devices. As shown in Figure 5, a ladder is incorporated at the tip of each boom to connect it to the membrane layers. To ensure that the ladder will not rotate during deployment, a traveling collar is added to act as an anti-rotation device. An inflation pressure of 7 psi particular inflatable sunshield design consists of four inflatable cantilevered booms and four layers of Kapton membranes, two located above and two located below the booms. In the stowed configuration, the booms were rolled up (see Figure 3) and the membranes z-folded. Controlled deployment of the booms was achieved by using was used to deploy the booms and membranes. After the sunshield was fully deployed, inflation pressure was increased to 15 psi to rigidize the aluminum laminate booms. The entire deployment process was extremely stable and the booms rolled out very straight. No noticeable configuration change of the booms was observed after the inflation/rigidization pressure was vented. Additional system design trades and

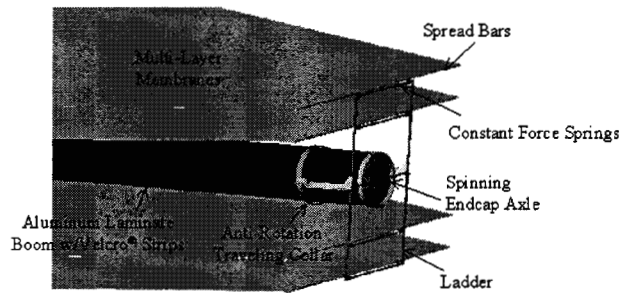


Figure 5. NGST Sunshield Ladder.

hardware fabrication details of the NGST inflatable sunshield engineering model are summarized in reference [20].

7. Inflatable SAR

Funded by NASA's Advanced Radar Technology Program (ARTP), JPL has developed a roll-up inflatable antenna array concept for synthetic aperture radar (SAR)

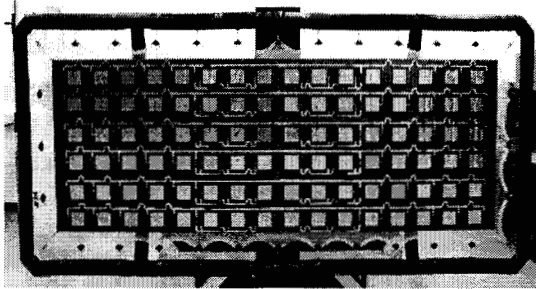


Figure 6. 1/3-Scale SAR Engineering Model from ILC-Dover.

applications [21 and 22]. This concept, known as the Inflatable SAR, utilizes an inflatable planar frame to support and stretch multiple layers of RF membranes. Two RF-functional inflatable SAR engineering models have been developed. The first model was a 1/3-scale model of a roll-up SAR antenna fabricated by ILC-Dover featuring a non-rigidizable inflatable planar frame with embedded

constant force springs for controlled deployment. This ILC-built model, see Figure 6, was tested in the JPL radar to successfully validate the overall mechanical and RF performance of the antenna. The second 1/3-scale engineering model, see Figure 7, was

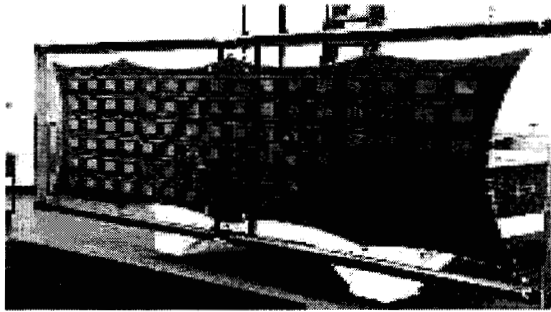


Figure 7. 1/3-Scale SAR Engineering Model from L'Garde.

built by L'Garde and featured longitudinal inflatable tubes that were made of a stretched aluminum laminate. Controlled deployment of this unit was accomplished by gluing Velcro[®] strips onto the stretched aluminum laminate tubes. The design and fabrication details of these two inflatable SAR engineering models can be found in [23 and 24], respectively.

8. Conclusion

Engineering models have been developed to successfully verify the feasibility of applying non-precision space inflatable structures to two selected space systems, namely the NGST inflatable sunshield and the inflatable SAR. Space demonstrations of these inflatable structural systems are also being planned. However, it is felt that the current R&D level of space inflatable structures technology is not sufficient to meet application goals for near-term space missions. The development of suitable space rigidization technology and effective dynamic modeling capability need to be accelerated. More importantly, focused and intensive R&D efforts need to be initiated to address other critical technical areas, including materials characterization, long-term space survivability of membrane materials, and the development of lightweight and compact inflation systems.

9. Acknowledgement

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